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14. ABSTRACT A ferromagnet/semiconductor based electrically controlled spin-current amplifier using a dual-drain non-local lateral spin valve was demonstrated. The spin polarization injected by the source into the channel was amplified at the second drain contact. An amplified current spin polarization of 100% was measured. The device provided controlled spin-current gain, which was varied in the entire range from -1 to +1. The controlled variation of amplifier gain with bias was also demonstrated. The maximum operating temperature of the device was as high as 150 K. <i>A pure spin-current generation with zero charge current was also demonstrated using this device.</i> This was the first experimental demonstration of a spin-current amplifier. The observations were explained in the framework of the spin drift-diffusion model. The principle of operation of the device was very generic and could be adapted to any ferromagnet/semiconductor heterostructure system.					
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Summary of Accomplishments (200 words max):

A ferromagnet/semiconductor based electrically controlled spin-current amplifier using a dual-drain non-local lateral spin valve was demonstrated. The spin polarization injected by the source into the channel was amplified at the second drain contact. An amplified current spin polarization of 100% was measured. The device provided controlled spin-current gain, which was varied in the entire range from -1 to +1. The controlled variation of amplifier gain with bias was also demonstrated. The maximum operating temperature of the device was as high as 150 K. *A pure spin-current generation with zero charge current was also demonstrated using this device.* This was the first experimental demonstration of a spin-current amplifier. The observations were explained in the framework of the spin drift-diffusion model. The principle of operation of the device was very generic and could be adapted to any ferromagnet/semiconductor heterostructure system.

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List of People Involved in, and Publications Stemming from, the Research Effort

- List of participants involved in the research effort

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- Archival publications (published) during the project period:

D. Saha, M. Holub, and P. Bhattacharya, "Amplification of spin-current polarization", *Appl. Phys. Lett.* 91, 072513 (2007).

D. Saha, M. Holub, D. Basu and P. Bhattacharya, "Spin-based memory using MnAs/GaAs multi-terminal non-local spin-valves", 52nd Magnetism and magnetic materials conference, Tampa, FL, Nov 2007.

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Comprehensive Summary of the Significant Work Accomplished

Electrical injection, control, and detection of large spin polarization in semiconductors are indispensable for the realization of useful spintronic devices. Electrical spin injection and detection have been demonstrated in all-metal devices¹ and ferromagnet/semiconductor based spin valves² having distinct coercivity difference between ferromagnetic spin injectors and detectors. Despite these advances, achievement of current spin polarizations of 100%, and effective electrical control of such polarizations have remained elusive. An electrically controlled spin-current amplifier is a desirable solution to this problem. Theoretical proposals for such devices have been made³, but experimental demonstration is lacking. Here we demonstrate an electrically controlled three terminal spin-current amplifier using a dual-drain non-local lateral spin-valve configuration, which can provide large polarization for both majority and minority spins, independent of the injected (source) polarization. The gain of the amplifier is varied electrically in the entire range from +1 to -1. A three terminal geometry is used for the device. The amplified output is extracted from the central terminal. The amplifier gain is precisely controlled through the input bias current and output extraction voltage. This device can be used to make spin-based memory and logic elements.

The principle of operation is based on spin injection and detection in semiconductors. When a current flows in a ferromagnet/semiconductor/ferromagnet lateral spin-valve, the electrochemical potentials of spin-up and spin-down electrons split in the semiconductor channel. The splitting depends on the relative directions of magnetization of the two ferromagnetic contacts. It is large when the two contacts (we call them source and drain1) are magnetized in opposite directions, and small (with a crossover in the center) when the contacts are magnetized in the same direction. A contact (drain2) is then placed at the center of the semiconductor channel of the spin-valve with anti-parallel magnetization of source and drain1 contacts, its potential is varied between spin-up and spin-down electrochemical potentials, enabling a controlled collection of spin-up and spin-down electrons. It is important to note that the two spin-currents flow in opposite directions and the current polarization is controlled by varying the current and drain2 bias. It is ensured that the drain2 contact acts as a high-impedance probe, so as to minimize any perturbation of the channel potentials.

Most Significant Advancements and Conclusions (include equations & figures as appropriate)

The schematic of a typical device is shown in Fig. 1a. The ferromagnetic source contact (S) injects a spin-polarized current into the non-magnetic GaAs channel through a Schottky tunnel barrier, which is collected at one of two ferromagnetic drain contacts (D1 and D2). The contact D2 is exactly centered within the effective channel between S and D1. Figure 1b schematically shows the relative orientation of magnetization in S, D1 and D2 as magnetic field B is swept. When B is large and negative, S, D1 and D2 are all aligned in the same direction as B (state M1). The contacts D2 (state M2), D1 (state M3) and S (state M4) then flip, in that sequence, as B sweeps through zero in the positive direction because of the relative magnitude of the coercivities. If a bias current (I_{bias}) is applied between S and D1 having parallel magnetizations, the electrochemical potentials for spin-up (μ_{\uparrow}) and spin-down (μ_{\downarrow}) electrons in the channel are split. In our devices, higher doping in the channel and lower bias operation lead to negligible drift, which causes the splitting to be anti-symmetric with respect to the center, $x = L_{\text{chan}}/2$.

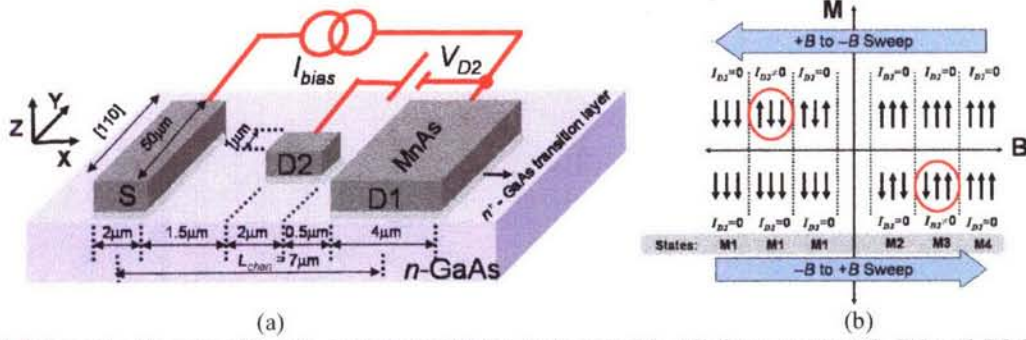


Fig.1 (a) Schematic diagram of a spin-current modulator (not to scale). All three contacts S, D1 and D2 have magnetic easy axes along the y direction (GaAs [110] direction). (b) The magnetization directions of the three ferromagnetic contact pads S, D1 and D2 as the magnetic field B is swept in both directions.

Hence, a bias voltage equal to the cross-over potential for spin-up and spin-down electrons in the channel can be applied at D2 ($V_{D2} = V_{null}$) to make current $I_{D2} = 0$ for states M1, M2 and M4 in Fig. 1b. However, I_{D2} will be non-zero under the same bias condition for state M3 where S and D1 are anti-parallel, for which μ_{\uparrow} and μ_{\downarrow} are split at $x = 0$. Under this condition the spin-up ($I_{D2\uparrow}$) and spin-down ($I_{D2\downarrow}$) components of current flow in opposite directions in D2. The spin-current modulation index (which can also be termed as normalized gain) and the current spin-polarization gain are defined as, $\Pi_{D2} = (|I_{D2\uparrow}| - |I_{D2\downarrow}|) / (|I_{D2\uparrow}| + |I_{D2\downarrow}|)$ and $\alpha_{D2}/\alpha_f = (I_{D2\uparrow} - I_{D2\downarrow}) / (I_{D2\uparrow} + I_{D2\downarrow})$, respectively, where α_f is the spin polarization of the ferromagnet. For a fixed I_{bias} in state M3, V_{D2} can be varied to control Π_{D2} . The modulation index can also be controlled with variable I_{bias} and $V_{D2} = V_{null}$.

Figures 2a and 2b show current I_{D2} measured as a function of in-plane magnetic field B (directed along the y axis) for different temperatures T ($I_{bias} = 100 \mu A$) and I_{bias} ($T = 10 K$), respectively. The voltage V_{D2} is set to the corresponding null voltages (V_{null}).

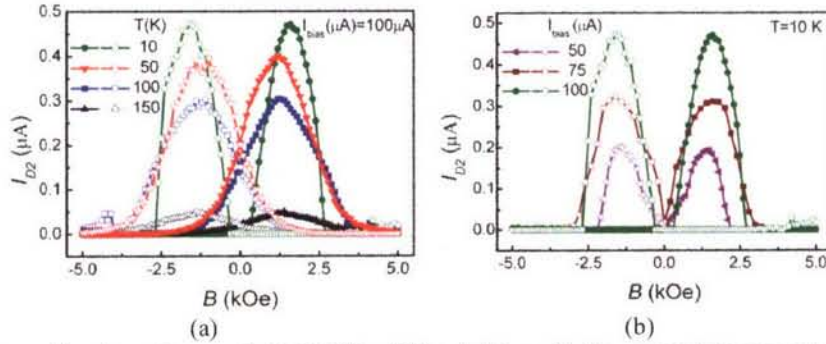


Fig. 2 (a) Current I_{D2} as a function of magnetic field B for different I_{bias} with V_{D2} set to their corresponding null values at 10 K. (b) Current I_{D2} as a function of magnetic field B for different temperatures T with $I_{bias} = 100 \mu A$ and $V_{D2} = V_{null}$.

A typical value for V_{null} at 10 K and $I_{bias} = 100 \mu A$ is ~ 21 mV. The peak of I_{D2} coincides with the peak anti-parallel alignment between S and D1 at $B = 1.5$ kOe, which corresponds to state M3 in Fig. 1b. The sign of current I_{D2} changes when the roles of S and D1 are reversed for the same value of B. The current decreases with increasing T and decreasing I_{bias} . The maximum temperature of operation is found to be 150 K for these devices. An increase in I_{bias} increases the operating temperature. Magnetoresistance measurements with conventional and non-local spin valves show a peak at the same value of B (not shown), which also confirms that I_{D2} is sensitive to the spin degree of freedom only. The symmetry of I_{D2} for large positive and negative values for B validates our assumption that the drift is negligible in our devices. No response is observed for the control devices, with a nonmagnetic D2 contact pad.

The experimental observations are explained by invoking the spin-diffusion (drift is negligible) model⁴. The spin-selective tunnel barriers are considered as spin-dependent resistances at low temperature and the spin-up and spin-down electrochemical potentials in the ferromagnetic metal MnAs are assumed to be the same. The solution of the coupled spin-diffusion equation for the spin-up and spin-down electrons in S and D1 lateral MnAs/GaAs/MnAs spin valves yields the electrochemical potentials in the channel as:

$$\mu_{\uparrow(\downarrow)} = \frac{jxe}{\sigma_n} + (-) \frac{2A}{\sigma_n} \left[\gamma e^{-x/\lambda_{sf}} + e^{(x-L_{chan})/\lambda_{sf}} \right] \quad (1)$$

where j is the current density in the channel, e is the electron charge, λ_{sf} is the spin-diffusion length in the channel, and γ is +1 (-1) when magnetizations of S and D1 are anti-parallel (parallel). It may be noted that the up- and down-stream diffusion lengths are equal as drift is neglected. The constant A is determined from the boundary conditions as:

$$A = \frac{j e \sigma_n}{8} \left[\frac{1 + \alpha_f}{G_{\uparrow}} - \frac{1 - \alpha_f}{G_{\downarrow}} \right] \left[\gamma + e^{-L_{chan}/\lambda_{sf}} \right]^{-1} \quad (2)$$

The current I_{D2} is then obtained as:

$$\frac{I_{D2}}{W_{D2}} = \int_{L1}^{L2} [G_{\uparrow} (V_{D2} - \mu_{\uparrow}/e) + G_{\downarrow} (V_{D2} - \mu_{\downarrow}/e)] dx \quad (3)$$

where $L1$ and $L2$ are the bounding x coordinates of contact pad D2. Figure 3a shows the measured peak I_{D2} as a function of I_{bias} in state M5 of the device. Theoretically calculated values of peak I_{D2} , using Eq. 3 and a value of $\lambda_{sf} = 7 \mu m$, are also shown alongside the measured data. The electrochemical potential difference between spin-up and spin-down electrons is plotted as a function of position along the channel in Fig. 3b. μ_{\uparrow} and μ_{\downarrow} remain anti-symmetric in the channel, making I_{D2} zero for all T and I_{bias} with $V_{D2} = V_{null}$, when magnetizations of S and D1 are parallel. On the other hand, when the magnetizations of S and D1 are anti-parallel, the difference $\Delta\mu$ decreases with decreasing I_{bias} and increasing T , which results in reduced I_{D2} in spite of increased tunnel conductance at higher T .

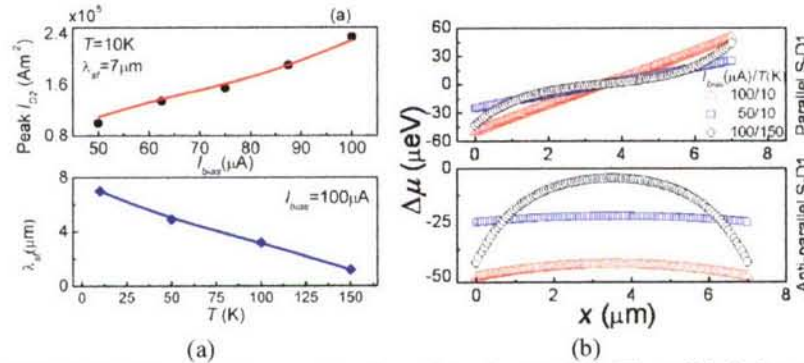


Fig. 3 (a) (upper panel) Peak drain2 current I_{D2} as a function of I_{bias} in state M3. The solid circles represent measured data at 10 K and the solid line represents the theoretically calculated values based on Eq. (3). The spin-diffusion length λ_{sf} is found to be $7 \mu m$ at 10 K (lower panel). (b) The anti-symmetric (symmetric) electrochemical potential difference between spin-up and spin-down electrons in the channel when S and D1 contact magnetizations are parallel (anti-parallel) for two different temperatures T and I_{bias} .

We next calculate α_{D2} and Π_{D2} as a function of I_{bias} and V_{D2} from measured values of I_{D2} . Figure 4a shows the current spin polarization gain α_{D2}/α_f and Π_{D2} as a function of V_{D2} for different I_{bias} . The curves shift along the V_{D2} axis with increasing I_{bias} due to the increasing value of V_{null} . Figure 4b shows the gain curves and Π_{D2} as a function I_{bias} for different values of V_{D2} . The plots show

that the magnitude and sign of both the gain and Π_{D2} can be varied by changing the value of I_{bias} and V_{D2} . The gain curves exhibit several singularities along the V_{D2} and I_{bias} axes. These occur when the charge current at D2, $I_{D2} = 0$ ($I_{D2\uparrow} = -I_{D2\downarrow}$), and a pure spin current, $I_{spin} (=I_{D2\uparrow} - I_{D2\downarrow})$, flows through this contact. The peak gain that can be measured is limited by the smallest possible increment of V_{D2} and I_{bias} around these singularities.

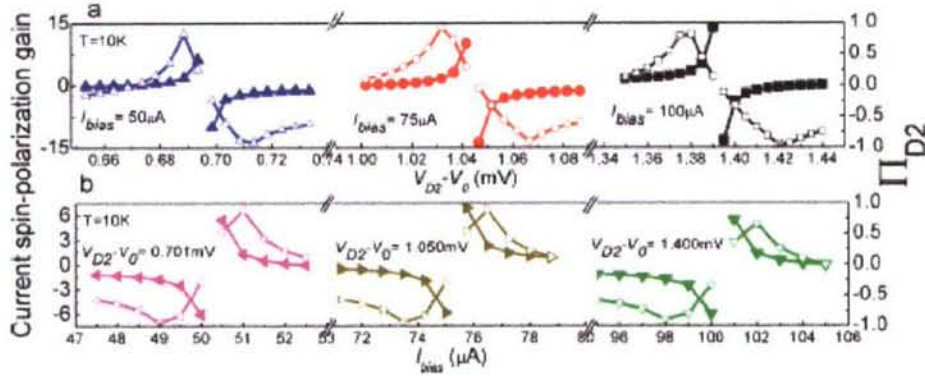


Fig. 4 Spin-current gain as a function of (a) D2 voltage bias V_{D2} , and (b) bias current I_{bias} .

A ferromagnet/semiconductor based electrically controlled spin-current amplifier using a dual-drain non-local lateral spin valve is demonstrated. The spin polarization injected by the source into the channel is amplified at the second drain contact. An amplified current spin polarization of 100% is measured. The device provides controlled spin-current gain, which is varied in the entire range from -1 to $+1$. The controlled variation of amplifier gain with bias is also demonstrated. The maximum operating temperature of the device is as high as 150 K. A pure spin-current generation with zero charge current is also demonstrated using this device. This is the first experimental demonstration of a spin-current amplifier. The observations are explained in the framework of the spin drift-diffusion model.

This device is used to realize a spin-based memory device. A schematic of the device and memory characteristics are shown in Fig. 5a and 5b, respectively.

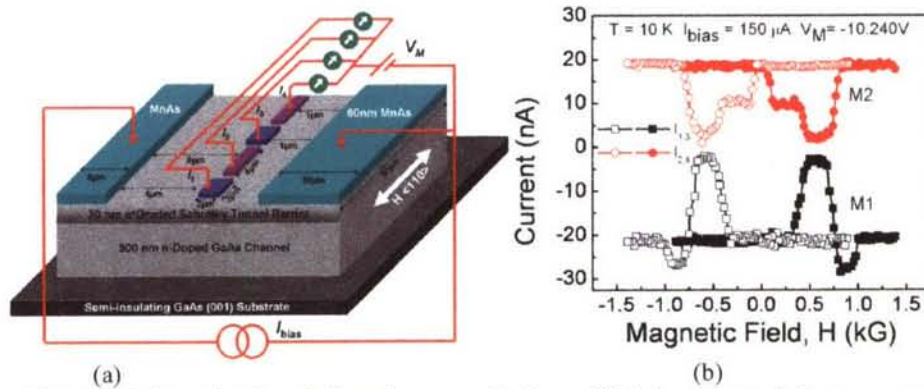


Fig. 5 (a) Schematic of a spin-based memory device, and (b) the characteristic response.

The memory is read-out by measuring the current through central drain-contacts (memory bits) as shown in Fig. 4b.

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